W134: A NEW PRE-MAIN SEQUENCE DOUBLE-LINED SPECTROSCOPIC BINARY [1]

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Abstract:

We report the discovery that the pre-main sequence star Walker 131 in the young duster NGC 2264 is a double-lined spectroscopic binary. Both components are (; stars with strong Li I 6708 Å absorption lines. Twenty radial velocity measurements have been used to determine the orbital elements of this system. The orbit has a period of 6,3,532:1 ().()()12 days and is circular within the limits of our velocity resolution; $e < 0.01$. The total system mass is $M\sin^3 i = 3.16\ M_\odot$ with a mass ratio of 1.04. Estimates for the orbit inclination angle and stellar radii place the system near the threshold for eclipse observability; however, no decrease in brightness was seen during two attempts at photometric monitoring. The circular orbit of W] 34 fills an important gap in the period distribution of pre-main sequence binaries and thereby constrains the effectiveness of tidal orbital circularization during the pre-main sequence.

1. Introduction

As the high-resolution spectral database for low mass pre-main sequence stars has expanded in the past decade, the 11111111)(7' of known pre-main sequence (PMS) spectroscopic binaries has steadily grown. V826 Tauri was the first to have a published orbit determination (Mundt *et al.* 1983). By 1988, three double-lined spectroscopic PMS binaries were known (Marschall and Mathieu 1988). The most recent tally (Mathieu 1992a) brings the number of single and double-lined PMS binaries to 20, including the current study. However, the number of short-period PMS binaries remains small, with only seven known to have periods of less than ten days. These young short-period binaries are an important observational constraint on theories of tidal orbital circularization (Mathieu and Mazeh 1988; Tassoul 1988; Zahn 1989; Zahn and Bouchet 1989; Goldman and Mazeh 1991; Mathieu *et al.* 1992). At issue is the question of to what extent do the processes of tidal circularization operate during the pre-main sequence phase of stellar evolution for low mass binaries. Zahn and Bouchet (1989) have asserted that tidal circularization occurs predominantly during the pre-main sequence phase for stars with periods up to about eight days. Thus, according to their theory, zero-age main sequence (ZAMS) low mass binaries with periods less than eight days should have circular orbits. Prior to the current study, the tidal circularization cutoff for solar- type pre-main sequence stars (defined as the longest period circular orbit; Mathieu *et al.* 1992) was set at 4.25 days by the binary ORI569 (Mathieu 1992a). However, until now there has been a gap in the periods of the known PMS binaries between 4.25 days (circular orbit) and 7.46 days (ORI429 - eccentric orbit; Mathieu 1992a), with the exception of the possible PMS eclipsing binary EK Cep (e= 0.1 I; period 4.4 days; Tomkin 1983).

Pre-main sequence spectroscopic binaries also provide constraints on the dynamical mass ratios in their systems, providing a check on the accuracy of theoretical PMS evolutionary tracks (Cohen and Kuhi 1979, Mazzitelli *et al.* 1989). However, only the double-lined systems enable the determination of the component mass ratios. Including the present study, there are now eight known double-lined PMS binaries (Mathieu 1992a). Recent data suggests that the dynamical mass ratios derived agree well with the placement in PMS tracks (Lee 1992), but the inclination uncertainty prevents determination of the absolute masses. Eclipsing binaries provide the most accurate stellar parameters; however, only one relatively "old" PMS eclipsing binary (EK Cephei) is known (Tomkin 1983; hill and Ebbinghausen 1984; Popper 1987). The existence of an extremely young PMS eclipsing system (age $\approx 10^6$ yrs) would provide masses and radii that could critically test the assumptions of current PMS stellar models.

In this paper, we report the discovery that the pre-main sequence star Walker 134 (also known as VSB 92; V=12.38; B-V= 0.84), located at $\alpha = 6^h 38^m 14.06^s$, $\delta = +09^\circ 58' 12.3''$ (1950) (or 95″ north of S Mon in the young cluster NGC 2264), is a double-lined spectroscopic binary with an circular orbit of period 6.35 days. The binarity of this system was serendipitously discovered in the course of a high spectral resolution study of abundances in low mass pre-main sequence stars in several star formation regions (Padgett 1991). W134 was first cataloged by Walker (1956) in a landmark stellar population study of the young open cluster NGC 2264. In a study of the proper motions of NGC 2264, Vasilevskis *et al.* (1965) give a 96% confidence estimate for W134's membership in the cluster. A spectral classification of G5 V was determined by Young (1978). Optical photometry of W134 is reported by Walker (1956), Mendoza and Gomez (1980), Sagar and Joshi (1983), and Feldbrugge and van Genderen (1991). Based on the differing V magnitudes found in these studies ($\Delta m_V \approx 0.3$), Sagar and Joshi suggest that W134 is a low amplitude variable. JHK photometry of W134 has been done by Strom and Hillenbrand (1993); they find J = 10.63 ± 0.01, H = 10.08 ± 0.02, and K = 9.81 ± 0.03. Finally, this object is a possible candidate identification for the 60 μm IRAS source PSC 06384+0958.

In the following we determine the orbital and physical parameters of the W134 binary system. In section III.1, the orbit solution, mass ratio, and M $\sin^3 i$ are determined from twenty high-resolution spectral observations. The effective temperature, ratio of component absorption line strengths, and lithium abundances are derived from the spectral database in Section III.2. We discuss the status of this system as a pre-main sequence binary in section IV.1, and the components are placed on the HR diagram using the available photometry in IV.2. The possibility that the system is an eclipsing binary is evaluated in IV.3. Finally, we explore the importance of this discovery in the context of binary tidal circularization theory in Section IV.4.

11. Observations & Analysis

Ten spectra of W] 34 were obtained using the echelle spectrograph on the Palomar 1.5m telescope over four separate observing runs during the period 1988 November to 1989 January. This instrument (McCarthy 1988) uses an unthinned TI 800 x 800 CC]) detector; with a].4" entrance slit, the effective spectral resolution R≈ 20,000 over the wavelength range **4000-8500"** Å. Multiple flat fields were taken using an internal continuum lamp, and averaged to a single flat for each night. On the dates of these observations a thorium-argon arc source was not yet internally installed, requiring that the entire instrument be removed for calibration. For this reason wavelength calibrations were performed only at the beginning ant] end of each run. These two calibrations were consistent to within 0.2 Å. Exposure times of 3600 seconds produced W1 34 spectra with a signal-to-noise ratio of 50 - 60 in the continuum.

Eleven additional spectra of W] 34 were obtained on consecutive nights during the period 1989 22 February - 04 March using the echelle spectrograph on the 2.5m Dupont Telescope at the Las Campanas Observatory. This instrument uses a "2-D Frutti" photon counting detector with several image tubes to amplify the spectrum. Using a 1.5″ entrance slit the effective spectral resolution was R≈ 30,000 over the wavelength range 3700-7000 Å. Flat fields were obtained using an internal LED to illuminate the detector. Thorium-argon arc spectra were taken before and after each exposure and their average was used for wavelength calibration. Due to the higher spectral resolution and lower overall efficiency of the Las Campanas echelle, and to detector count rate limitations, exposure times of 7200 seconds were needed to yield spectra with a signal-to-noise ratio of 40 - 50 in the continuum for W134.

The raw spectra were processed with the echelle reduction routines in the *Figaro* software environment. Curvature in the raw orders was removed with the *sdist* routine. This "S distortion" was fairly stable in the Palomar data, but in the Las Campanas spectra it varied enough to require individual fits to the curvature of each spectrum. The *echtract* routine was then used to subtract scattered light and reduce each of the forty orders to a single row of data. Next the arc spectra were wavelength-fitted by the *echarc* routine using a table of 1200 Th-Ar lines and interactive identifications of selected lines. The wavelength fit was quite stable in the Palomar data, but proved to be somewhat variable in the Las Campanas spectra. The arc fits were applied to the spectra of W134 using the *echxrebin* routine. The final steps of continuum normalization and equivalent width measurement were done using the NOAO *IRAF onedspec* routines *continuum* and *splot*.

Cross correlations of the 1988 November and January 5, 1989 Palomar W134 data were performed using the K0 star HR 1136 as a template for six echelle orders from 5800 to 6700 Å excluding the orders containing Hα, [O I] 6300 Å, and the Na D lines. The heliocentric radial velocity of HR 1136 was approximately determined by cross-correlation of its spectrum with a spectrum of BP Tau (V_r = 15.8 ± 1.0 km s^{-1} heliocentric; Hartmann *et al.* 1986). The resulting radial velocity for HR 1136 is -7 ± 3 km s^{-1}, which agrees with 111(' valueof -6 Ii Ill s^{-1} ill the Bright Star Catalog ue. Unfortunately, no radial velocity standards were observed dill'illg the Palomar observing runs on December 22, 1988 and January 20, 22, 25, 1989. For these observations separation velocities only were obtained (marked with an L in Table 1). The Las Campanas data were cross- correlated with the weak-line K2 T Tauri star KM Orionis. The radial velocity Of KM Ori was determined via a cross-correlation Of its spectrum with P1270 (v_r = 26.1 km s^{-1}; Hartmann *et al.* 1986); we find v_r (KM Ori) = 22.7 ± 2 km s^{-1}, which is consistent with its kinematic membership of the Orion association, For all the observations, separate cross-correlations were performed for each of the six echelle orders. The peak centers were determined using the IRAF program *fxcor* with typical errors of 4 km s^{-1} in the centering routine. These relatively large errors result from the spectral type mismatch of the binary and template spectra, as well as the only moderate S/N in the W134 spectra. The standard deviation of the mean component velocities over the six echelle orders was adopted as the radial velocity uncertainty. The deblend routine within *fxcor* was used to separate the blended components when the separation velocities were less than 50 Ii Ill s^{1}. The mean peak positions over the six orders were then adopted as the component velocities with respect to the template objects. Corrections for Earth orbital motion and the template star radial velocity were applied to the final results listed in Table 1.

The radial velocity data were analyzed for an orbit solution using the program 1"1-'1'01{1) which was written specifically for this project. FITORB performs a non-linear least-squares fit to the radial velocity equation

$$\frac{dz}{dt} = \frac{''('r's]'''}{(1 - e^2)^{1/2}} (e\cos\omega + [.os(1)-\{\omega)) + V_{sys} \quad (1)$$

(Taff, eq. 1 3.4), where n is the mean motion, a the semi-major axis, i the orbital inclination to the line of sight, e the eccentricity, w the argument of periapse, v the true anomaly, and V_{sys} is the systemic velocity of the binary. The relationship between v and the time of an observation t is given by the equations

$$E - e\sin E = n(t - T_p) \qquad \cos v = \frac{(\cos E - e)}{(1 - e\cos E)} \tag{2,3}$$

(Taff, eqs. 2.8 & 2.10), where T_p is the time of periapse and E the eccentric anomaly. FITORB solves for the parameters $n, a\sin i, e, \omega, T_p$, and V_{sys} given either individual component velocities or the separation velocity; data points were weighted according to the inverse of their velocity uncertainty. Conversion between observed and heliocentric radial velocities was performed using routines from the JPL Navigation Ancillary Information Facility (NAIF) software toolkit (Acton 1990). FITORB was tested using synthetic radial velocity datasets. It was also tested using the data for the pre-main sequence binary 160905-1859 presented by Mathieu *et al.* (1989), and converged identically to their solution when provided with a good initial guess for the period.

111. Results

a. Dynamical Properties

Orbit model fits were performed using the radial velocity data for each component of W134 and for the separation velocity. Due to uncertainty in our absolute velocity calibration, the separation velocity solution proved to be better (in the chisquared sense) than either of the individual component fits. We therefore adopted values for the period ($P = 2\pi/n$), e, ω, and T_p given by the separation solution and fixed these values in a re-solution of the individual stellar orbits. The individual component velocity data then yielded the mass ratio and systemic velocity of W1 34. The overall solution gives a very small eccentricity ($e = 0.0004 \pm 0.0007$) and coil'('s])ollclillgly large uncertainties in the values for ω and T_p. For comparison we then fit the data with a zero eccentricity model. We found no significant difference (in the chisquared sense) between the circular orbit solution and the original solution where e was permitted to find its optimum value. Thus we conclude that the orbit is circular within the limits of our radial velocity data. The adopted orbital elements are shown in Table 2.

The radial velocity data points are plotted in Figure 1 along with the adopted orbit solution. These values can also be found in Table 1. Errors in the absolute velocity calibration are evident in the individual component fits: the observed velocities of both components appear systematically offset from the orbital solution at phases of 0.288, 0.718, and 0.792. However, the fact that these three points are not discrepant in the circular orbit separation velocity fit shows that the relative velocity calibration is reasonably good. This justifies our use of only the separation velocity data in our determination of the period and eccentricity. Note that the systemic velocity we determine for W134 (25.8 ± 1.0 km s^{-1} heliocentric) agrees fairly well with the systemic velocity of NGC 2264 (21 ± 5 km s^{-1}) determined by Perez (1991).

b. Physical Properties

Effective temperatures were determined for the components of this binary by using spectroscopic line ratios calibrated against spectral standards of known temperature. Spectroscopic line ratios have been used to determine spectral types of double-lined binaries by Boesgaard and Tripicco (1987); they have also been applied to the problem of classifying pre-main sequence stars by Basri and Bertout (1989) and Padgett (1991,1994a). The method involves obtaining temperature-sensitive line ratios for spectral standards of known temperature, fitting the relation between T_{eff} and the ratios via linear regression, and then using this fit to determine temperatures of PMS stars from their line ratios. The details of this method are thoroughly discussed in Padgett (1991,1994a). However, few of the line ratios used in these previous studies were measurable in the case of W134. As the two components orbit, their absorption lines move ± 3 Å, causing considerable blending and confusion in line identification from night to night. As a result, the V I λ6199 to Fe I λ6200 line pair was the only one of the six used in Padgett (1994a) which remained measurable on most nights. The equivalent widths of V I λ6199 and Fe I λ6200 were measured on all spectra; however, on some nights the line pair was not identifiable for both components due to confusion with other absorption features and an ill-placed detector flaw on the Palomar spectra. The temperature determined for component A is a mean over ten nights of observations; the one for component B is a six night average. The derived temperatures are, for component A: $T_{eff} = 5500 \pm 130$ K; and for component B: $T_{eff} = 5350 \pm 300$ K. As the errors in these values imply, the line ratio of V I J6199 to Fe I λ6200 varied considerably for component B from night to night. These changes in apparent temperature are apparently not correlated with changes in the relative strengths of the cross-correlation peaks, although the small number of data points makes determining any pattern difficult. Nevertheless, it is possible that these two effects may both be a consequence of starspots on component B, since neutral vanadium lines are especially sensitive to temperature and are enhanced in sunspot spectra.

Lithium abundance determinations for each component were performed on the resonance doublet of Li I λ6708 using the spectroscopically determined effective temperatures. The equivalent widths of the λ6708 line were corrected by the ratio of the blackbody fluxes at this wavelength and assuming that the radii of the two components are identical, as in Boesgaard and Tripicco (1987). For component A, the 12 night mean of the measured $W_{6708}(A) = 0.20 \pm 0.03$ Å and $W_{6708}(B) = 0.17 \pm 0.03$ for component B. The corrected equivalent widths are 0.37 Å for component A and 0.36 Å for component B. The log g of both components was fixed at 3.8, and the microturbulence set to be 1.8 km s^{-1}, both typical values for pre-main sequence stars as determined by Padgett (1991,1994a). Curves of growth were calculated with the program RAI10 (courtesy of A. Boesgaard) using solar [Fe/H] model photospheres from Gustafsson (1988). With these assumptions, the derived logarithmic lithium abundances on a scale with logN(H) = 12.0 are logN(Li) = 4 for component A and logN(Li) = 3.8 for component B with errors of approximately ± 0.4 dex from uncertainties in the temperatures and equivalent widths. Among weak-lined T Tauri stars, the mean lithium abundance found by Padgett (1991,1994b) is logN(Li) = 3.6 ± 0.3, with some even larger values in a few stars. The very high Li abundance derived for W134 matches the value N(Li) = 4.0 ± 0.2 dex found for the NGC 2264 PMS star G-G 405, and is among the larger lithium abundances determined for the low mass PMS stars in the Taurus-Auriga, Orion, Chamaeleon I, and Ophiuchus T Tauri associations (Padgett 1994b).

The more massive component in the W134 binary system has deeper absorption lines than the secondary. The ratio of the area under the cross-correlation function (CCF) peaks W_A/W_B has a mean value of 1.32 ± 0.17. The ratio obtained for individual observations ranges from 1.12 to 1.64. The maximum values for this ratio were obtained during the first observations in November 1988; however, during the run of 11 consecutive nights at Las Campanas in February-March 1989, W_A/W_B varied from 1.2 to 1.5, changing by as much as 0.3 on a timescale of one day. Figure 2 plots the ratio of the component CCFs versus the orbital phase of the binary. No clear pattern emerges, although the highest values are noted between phase of 0.1 and 0.4. In two stars of equal temperature, the ratio of the area under the cross-correlation function for the two components has been interpreted as the luminosity ratio (Reipurth *et al.* 1990). For a CCF ratio of 1.3, the radii should differ by a factor of 1.14. However, the large and unexplained night-to-night variation of this ratio demonstrated in Figure 2 renders the derivation of stellar properties using the CCF ratio questionable in the case of W134. Variability in the CCF ratio for other PMS binaries has been attributed to spots (Reipurth *et al.* 1990), and obscuration by circumstellar dust (Andersen *et al.* 1989). In the case of W134, the paucity of data makes it difficult to adopt either of these models.

With our relatively poor velocity resolution (15 km s^{-1}), the absorption spectrum of W1 34 appears only slightly broadened with I'('s])('('t to the template spectrum. The approximate $v\sin i$ of the W1 34 components was obtained by comparing the FWHM of the W1 34 cross-correlation peaks wit]] a grid of FWHM derived from cross-correlations between a template spectrum and the same template broadened by a rotational function (Gray 1976). We obtain ,alucsof18 $\pm$ 5 km s^{-1} for both of the components of the W1 34 system. Using the orbital period and stellar radii derived in Section IV.2, we find that the synchronous rotation rate is about 25 km s^{-1} . If this system is tidally locked, the inclination angle implied by the $v\sin i$ is $46^{\circ} \pm ^{21}_{15}$.

IV. Discussion

1, The Pre-main Sequence Nature of W134 A ant] B

There are several factors which reaffirm the pre-main sequence nature of W134 A and B. First, its position in the sky places it squarely in the midst of the extremely young open cluster NGC 2264 . The proper motion of W134 is sufficiently close to the bulk proper motion of NGC 2264 that Vasilevskis *et al.* (1 965) assign a 96% probability of of cluster membership. Finally, the systemic radial velocity we determine for W1 34 (25.8 $\pm$ 1.0 km s^{-1}) is in agreement with the radial velocity of the NGC 2264 cluster (21 $\pm$ 5 km s^{-1}; Perez 1991). Thus the location and kinematics of W134 firmly establish its membership in NGC 2264. The age of NCG 2264 has been determined as 3×10^{6} yr by the main sequence 'till'llOf~ of 011 stars (Walker 1 956); therefore, W] 34 is a member of a very young stellar association with ongoing low mass star formation.

The components of W1 34 display photometric and spectroscopic characteristics common to low mass pre-main sequence stars. The neutral lithium resonance doublet at 6708 Å, a identifying spectral feature for all low mass PMS stars, is detected strongly in both components of W1 34. The lithium abundance which is derived for these stars using the 6708 A line (log[N(Li)]= 4.(1) is at the upper edge of the envelope for lithium values in pre-main sequence stars (Padgett 1994b; Maguzzu *et al.* 1992; Basri *et al.* 1991). Although lithium depletion occurs more slowly for stars of $\geq$ 1.0 $M_\odot$ than for lower 111{1SS stars (Michaud 1991), ZAMS stars in young clusters with the same mass as the components of W134 generally have a lithium abundance of N(Li) = 3.2 dex or lower. However, abundances found for weak-line T Tauri stars may range from 3.0 to $\geq$ 4.() (Padgett 1994b; Maguzzu *et al.* 1992; Basri *et* 01. 1991; Strom *et al.* 1989). Thus, the strength of the lithium line in both components of W134 supports their status as extremely young objects.

Furthermore, the spectrum of the W134 binary displays Hα and calcium 11 and K emission lines characteristic of weak-line T Tauri stars. The strength of the Ca 11 emission line is similar for the two components and little variability in the lines was observed over 11 consecutive nights. In contrast, the strength and structure of the Hα emission feature changes dramatically over the same period of time, varying from an inverse P Cygni profile (Fig. 3, bottom) to a pure *single* absorption (Fig. 3, top) even when the components are well-separated. The Hα equivalent width varies from 0.5 to 1 Å; the corresponding Hα luminosity log[$L_{H\alpha}$ ($L_\odot$)]= -3.4 is typical of weak line T Tauri stars (WTTS) such as LkCa 4 (Cabrit *et al.* 1990). The relatively broad nature of the line as well as the variability of the embedded absorption features suggest that Hα emission in these stars may not be])111"('IJJ chromospheric. The PMS binary 162814-2427 also shows evidence of weak inverse II) Cygni Hα emission, which has been interpreted as evidence for accretionary processes (Mathieu 199'21)). of the! known PMS short-period binaries, only V4046 Sgr has a strong Hα emission line, possibly indicating that close binaries tend to disrupt the inner accretion disk where the strong Hα emission lines of classical T Tauri stars is thought to originate (Mathieu 1992b). It is interesting to note that the near-infrared excess (Fig. 4; see below) of W] 34 is more typical of classical T Tauri stars than WTTS. In this way W1 34 is similar to the PMS spect roscopic binary AK Sco (Andersen *et al.* 1 989) which also has weak optical emission lines.

2. Placement in the HR diagram

UBVRI photometry of 11'134 is presented by Mendoza and Gomez (19S0). The reddening of W134 is small: Young (1 978) studied the distribution of E(B-V) in NGC 2264 and finds a value of E(B-V)= 0.08 for W134. We have recalculated the reddening using a mean spectroscopic temperature of 5450 K, and find a value of E(B-V)= ().2(). Using this value to deredden the photometry of Mendoza and Gomez, extrapolating into the infrared using a 5450 K blackbody normalized to the photometry at 1 band, and using a distance to NGC 2264 of 700 pc (Feldbrugge and van Genderen 1991), we derive an an integrated luminosity of 16.1 $L_{\odot}$ for the system. This luminosity must be considered uncertain by 25% due to the observed variability of \3'134 and the lack of simultaneous photometry. The dereddened spectral energy distribution of W] 34 is shown in Figure 4. The clear near-infrared excess is many times larger than can be accounted for by starspots, even for 50 % surface coverage. This excess is more typical of c.lassie.al T Tauri stars, and indicates that warm dust is present within 0.3 AU of the binary. Dust grains smaller than 1 mm in size are removed from this region by Poynting-Robertson drag in only 10^4 years; new material must therefore be constantly supplied. The reservoir for this material could well be a circumbinary disk. At least four other short-period PMS binaries also show evidence of circumstellar disks in their spectral energy distributions (AK Sco, V4046 Sgr, I(i2814-2427, 1 62819-2423S; Mathieu 1 992b), and some show evidence of an evacuated central hole in the dust distribution. The determination of the disk structure around the W1 34 binary will require additional IR observations to extend the spect ral energy distribution to longer wavelengt 11s.

According to the pre-main sequence evolutionary tracks of Mazzitelli *et al.*, stellar luminosity scales as $L \propto M^{2.6}$ in the region of the HR diagram appropriate to W134. Using the mass ratio determined from the orbit solution and this luminosity scaling law, we find that component A should be 12% more luminous than component B. Thus the estimated individual luminosities are $L_A = 8.5\ L_\odot$ and $L_B = 7.6\ L_\odot$. These values allow radius estimates to be made according to the equation $L = 4\pi\sigma T_{eff}^4 R^2$: we find comparable radii $R_A = 3.2 \pm 0.5\ R_\odot$, $R_B = 3.2 \pm 0.7$. When placed in the HR diagram (Figure 5), both components appear below the birthline in a region well-populated by other members of NGC 2264 (Palla and Stahler 1990; Stahler 1985).

From the location of W134 in the HR diagram, the mass and age for each component can be estimated via comparison with predicted pre-main sequence evolutionary tracks and isochrones. The tracks of Mazzitelli (1989) give $M_A = 2.3\ M_\odot$, $M_B = 2.2\ M_\odot$, and ages of 2×10^6 yrs. However, the uncertainties in luminosity and T_{eff} combine to give a 10% uncertainty in the theoretical masses and 10^6 yrs in the theoretical ages. The theoretical masses imply that W134's orbit is inclined by $\sin^{-1}(3.16/M_A + M_B)^{1/3} = 63° \pm 4$.

3. Possibility of Eclipses

The maximum inclination angle for which eclipses *do not* take place in a binary system is given by simple geometry:

$$\tan i = \frac{a \sin i}{R_A + R_B} = \frac{21.2}{6.4 \pm 1.2} \tag{3}$$

For the parameters of the W134 system, this limiting angle $i = 73° \pm 3$. If the orbital inclination inferred from the PMS tracks is correct, the likelihood of observable eclipses is therefore small. However, the uncertainty in the theoretical tracks is sufficient to allow the possibility of grazing eclipses. Photometry during zero velocity separation events in 1989 found no diminishment of the light from this system; however, the photometry was only good to 10% and the orbit was less well cons rainedthan that presented 11('1"('. If central, the eclipse duration would be 7.4 hours. Furt iemonitoring of thesystemis 11['('(1('(1.

4. Importance for Tidal Circularization Models

The orbital evolution of close binaries has recently been a topic of considerable interest to both the observational and theoretical communities. One important result of recent observational studies has been the discovery that coeval binaries in open clusters have a eccentricity transition period below which the binaries have circular orbits and above which they have measurable eccentricities. This transition or '(cutoff) period is 5.7 days for the young Pleiades, Coma, Hyades, and Praesepe clusters (Mayor and Mermilliod 1984), but illcl'cases to more than 10 days in the case of the much older M67 cluster (Mathieu *et al.* 1988). The increase in the cutoff period with age has been interpreted as the result of tidal circularization processes which slowly reduce the eccentricity of binary orbits during their main sequence lifetime. A variety of theories have been proposed which predict the magnitude of tidal circularization effects during the main sequence (Zahn 1966, 1977; Alexander 1973; Lecar, Wheeler, and McKee 1976; Hut 1981; Tassoul 1988). This interpretation has led to the proposal by Mathieu and Mazeh (1988) that the value of the transitional period could be used as a "clock" to determine the age of open clusters once the normalization of the tidal circularization timescale is understood. However, two articles by Zahn (1989) and Zahn and Bouchet (1989) challenge the entire notion that tidal effects mainly operate on the main sequence. They point out that most of the proposed tidal circularization processes are much more effective in the fully convective envelopes of pre-main sequence stars and conclude that all binaries $(0.3\ M_{\odot} \leq M_{*} \leq 1.25\ M_{\odot})$ with periods of less than eight days will be circularized by the time they reach the mainsequence. Goldman and Mazeh (1992) have responded by questioning the applicability of the mixing length theory used by Zahn's models. In addition, expansion of the observational database confirms the a definite increase in cutoff period between the youngest clusters and 01(1('1" cluster and halo stars (Mathieu *et al.* 1 {)92). However . the subject remains controversial.

From an observational standpoint, the determination of the transition period for pre-main sequence binaries of various masses will provide an important test for all the theories in question. The cutoff' period between circular and eccentric orbits for PMS stars determines the initial conditions for main sequence orbital circularization. Main sequence binaries with circular orbit periods longer than the PMS cutoff are evidence of main sequence tidal circularization processes. Recently, the tidal circularization cutoff period for a coeval group of binaries has been defined as the longest period circular orbit, which is generally, but not always, longer than the shortest period eccentric orbit (Mathieu *et al.* 1 W?). In a recent review of PM S spectroscopic binaries, Mathieu (1 992a) set the proposed PMS transition period at 4.25 days, the period of OR1569's circular orbit. All solar-type PMS binaries with longer periods known at that time had measurable eccentricities, including EK Cep (period 4.4 days; e = ().1 1) and ORI429 (period 7.46 days; e = 0.31). The gap in known PMS binary periods between 4.4 and 7.46 days has created considerable uncertainty in the value of the PMS cutoff. The range of possible cutoff values has considerable importance in distinguishing between the models of tidal circularization operating, primarily during the pre-main sequence (i.e. Zahn and Bouchet 1989) which argue for cutoff period of 7-8 days and theories which emphasize tidal evolution during the main sequence (*i.e.* Mathieu *et al.* 1992) which favor shorter PMS cutoffs.

The discovery of the W1 34 binary fills this important gap in the period/eccentricity distribution of PM S binaries. W1 34's orbit has the longest period circular orbit among close PMS binaries; thus, it suggests a new value of 6.35 clays for the pre-main sequence star tidal circularization period. The classical T Tauri star GW Ori is a single-lined binary with a period of 243 days and eccentricity of ().()43 0.06 (Mathieu, Adams, and Latham

1991); however, the separation of its components is too large for tidal processes to have been significant in circularizing the orbit. W134 therefore has the longest period of any pre-main sequence binary with a well-determined circular orbit and where tidal circularization is likely to have been effective. The 6.35 day value is reasonably consistent with the 8 day cutoff period for pre-main sequence tidal circularization derived numerically by Zahn (1989).

However, there are a number of problems with using the W134 binary as the cutoff period point for solar-type PMS stars. The dynamical masses implied for this system probably exceed 2 $M_\odot$ for each component. Despite their relatively late spectral types, the W134 stars are closer to intermediate mass than low mass stars, and are considerably more massive than the stars modelled by Zahn and Bouchet (1989). Those models show a trend of decreasing circularization time between stars of 0.5 and 1.25 $M_\odot$. As mass increases still further, at some point the lack of time spent on the PMS with a fully convective envelope should negate the processes discussed in Zahn and Bouchet (1989), and eccentricity should persist in short-period binaries as is seen in early-type main sequence stars. Indeed, in main sequence A stars, which the components of W134 will eventually become, there is no tightly constrained cutoff period; circular orbits are found with period of up to 10 days, while some eccentric orbits have periods as short as 3.3 days (Matthews and Mathieu 1992).

An additional complication is the eclipsing binary system EK Cep, which has a measurable eccentricity of 0.11 in its 4.4 day period orbit (Tomkin 1983). As a presumed PMS binary with an eccentric orbit having a *shorter* period than the PMS cutoff of 6.35 days set by W134, this system is important in defining the width of the transitional period region caused by the distribution of initial eccentricities. The pre-main sequence status of EK Cep B is suggested by a variety of photometric and spectroscopic evidence. Popper (1987)

]Ias ('011 ('111(1('(1 thatthe A I primary (2.1$M_\odot$) ill this system is approximately zero-age main sequen ce, while the secon dary is 1 .12 $M_\odot$ with temperature and luminosity which place it slightly above the main sequence (age 2-3x10^7 years on the tracks of Mazzi telli (1{)89)). Additional evidence for the secondary's youth is its large radius and subsequently low surface gravity in comparison to similar main sequence stars. Popper also used the presence of a photometric excess in the blue to justify his classification of the secondary as a pre-main sequence star; however, current theory links the presence of blue and UV excesses in PMS stars to the presence of accretion disks, which is highly unlikely in EK Cep due to its lack of reddening and the absence of spectral signatures of disk accretion. One of the most reliable spectral indicators of stellar youth is the presence of a strong Li I6708 A absorption. Previous studies of lithium abundances in pre-main sequence solar-type stars have found strong lithium resonance lines for all stars of type G0 - K5 (Padgett 1994b). The presen ce of the 6708 Å feature is considered to be an identifying PMS feature, especially for the Weak-]i]lcc] stars without prominent emission lines. Martin and Rebolo (1993) have measured a strong lithium resonance line in EK Cep B and has derived a lithium abundance of log N(Li) = 3.1 for this star, which is similar to values fou nd in for the youngest main sequen ce ("lush stars. Despite EK Cephei's lack of positional or kinematic assoc iation with a star-forming cloud or young cluster (Popper 1987), present evidence suggests that EK Cep B is indeed an '(older" pre-main sequence star close to the main sequence. If EK Cep's PMS identification is correct, the significance of its elliptical orbit having a shorter period than W134 may reflect a high initial eccentricity or the presence of an as yet undetected third star in the system. Alternatively, the large difference in mass between the primary and secondary, and subsequent differences in pre-main sequence history, may have influenced the tidal evolution of this system (Mathieu *et al.* 1992). Finally, the relatively large mass of the EK Cep primary, as well as the components of W134, may indicate that these systems are not subject to the clear tidal cutoff period seen in fully convective low-mass stars; a large overlap in short-period eccentric orbits and long-period ("ii'(llIal' orbits is present among the main sequence stars of type A and earlier (Matthews and Mathieu 1992).

v. Conclusions

(1) W134 is a double-lined spectroscopic binary with a circular orbit and a period of 6.353 clays.

(2) W134 is unquestionably a pre-main sequence system of age < 3 x 10^6 yrs, as indicated by its membership in NGC 2264, location in tl ıe 1 1 1 { diagram, high lithium abu nda nce log[N(l ,i)]= 4.0, Hα emission, and near-infrared excess. 'ill ıe star's emission line properties are typical of weak line '1' 'Tauri st ars, whereas its observed near-infrared excess is more typical of classical T Tauri stars.

(3) W134 has the longest period of any pre-main sequence s]wctmsc.epic binary with a well-cletcll))il]tncl circular orbit. Its 6.353 day period constrains the transition period between eccentric and circular orbits for pre-main sequence stars with masses of 2 $M_\odot$.

(4) Further studies of W] 34 are needed. The system should be monitored for p ossible eclipses, as current estimates for the inclination angle and stellar radii indicate that the system geometry lies near the threshold for observable eclipses. Furthermore, the large velocity amplitude and short period of the W134 binary imply that the best correlation spectroscopy techniques should be able to determine the orbit to very high accuracy.

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Figure Captions

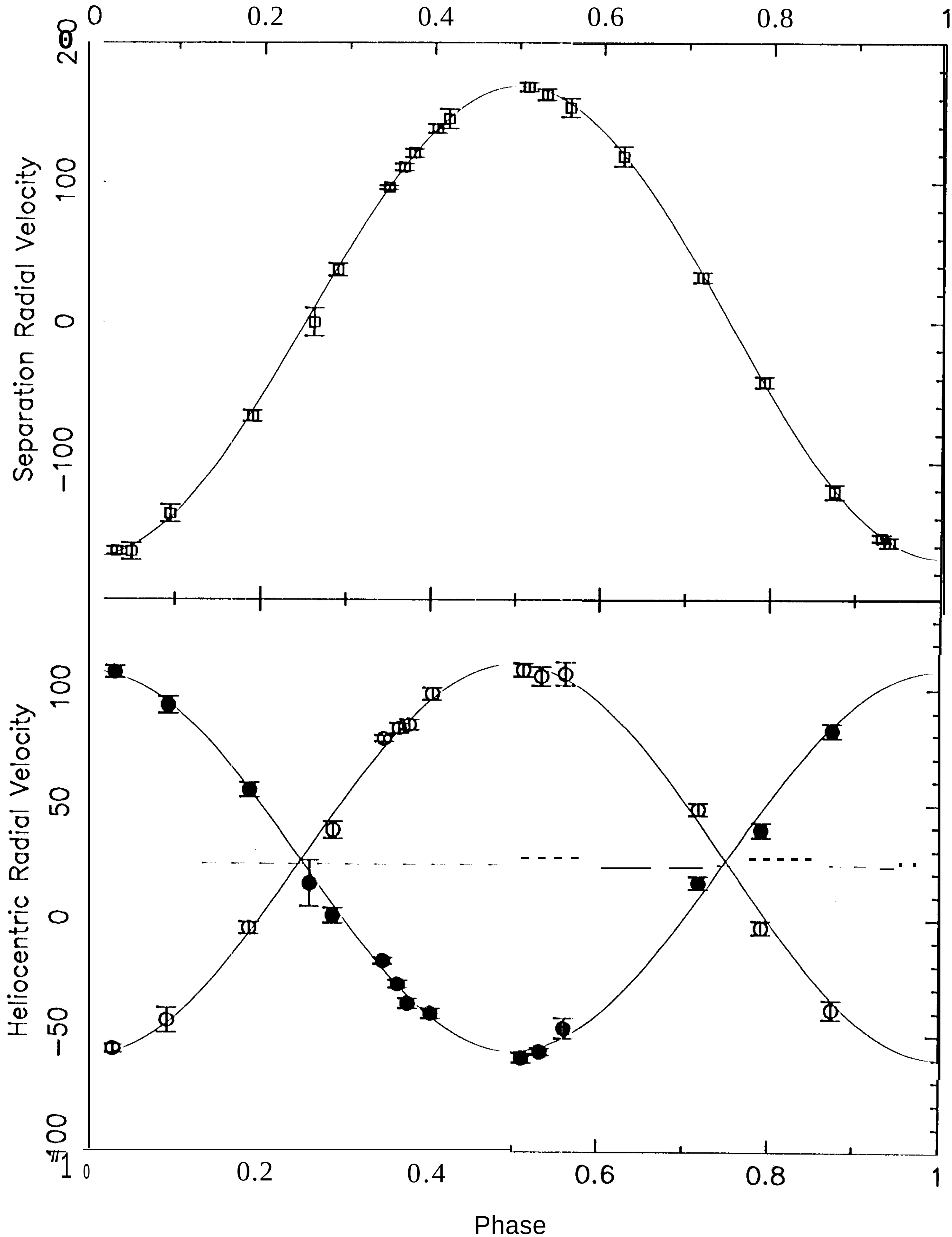
Figure 1. Phase plots of the Orbit of W134. The upper panel shows the observed separation velocity ($V_S = V_B - V_A$) data points plotted against the orbit solution (solid line). Zero phase occurs at T_0 (see Table 2). The lower panel shows the heliocentric radial velocity data for the individual components (A: find circles, B: open circles) and the individual orbit solutions. The dashed line marks the systemic velocity of the binary.

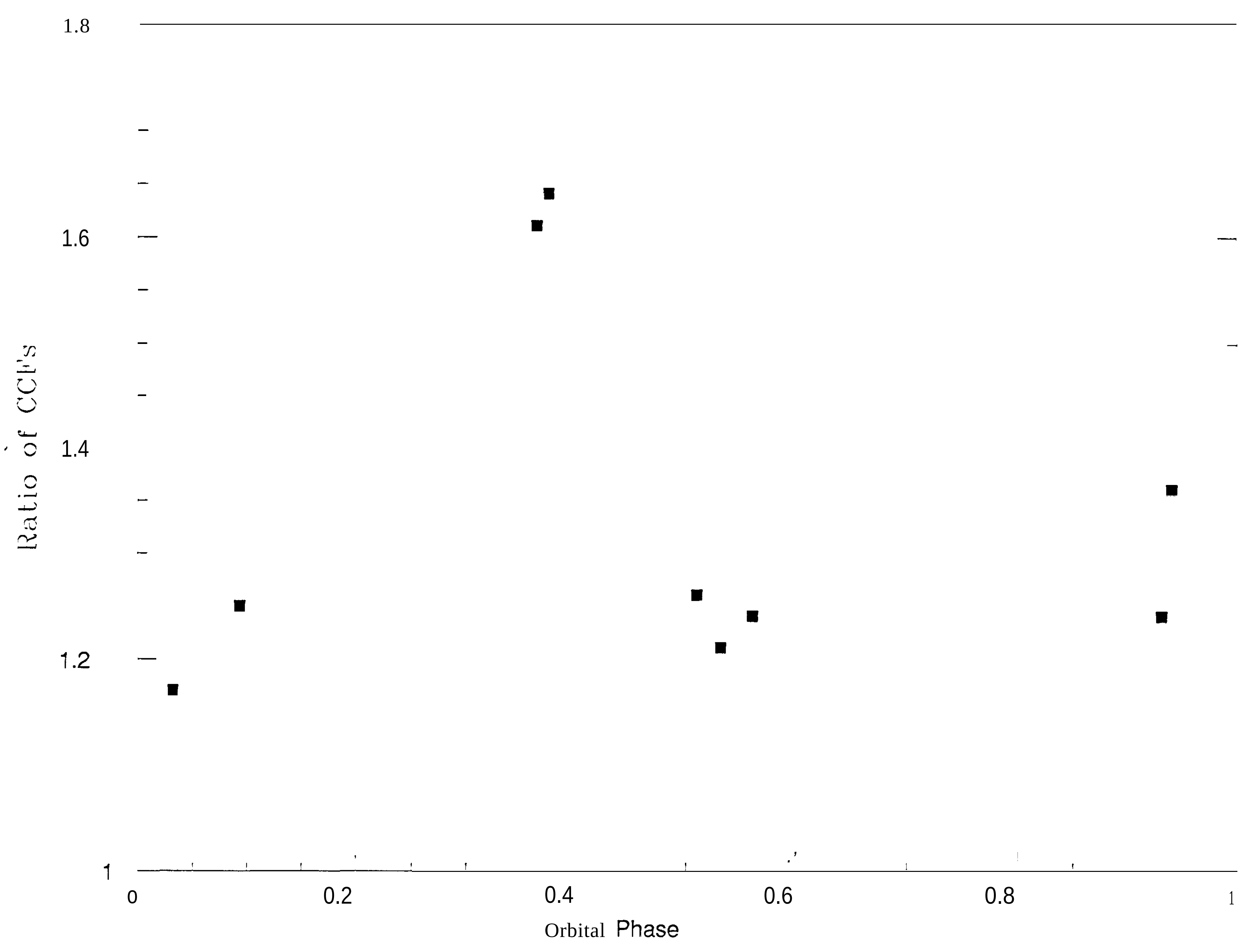
Figure 2. Ratio of the area under the cross-correlation function (Component A /Component B) versus orbital phase.

Figure 3. Hα emission in the spectrum of W1 34 on five consecutive nights at Las Campanas. Wavelengths corresponding to the individual component velocities on these nights are indicated; the middle spectrum is a zero velocity event. The vertical line marks the rest Velocity of the system.

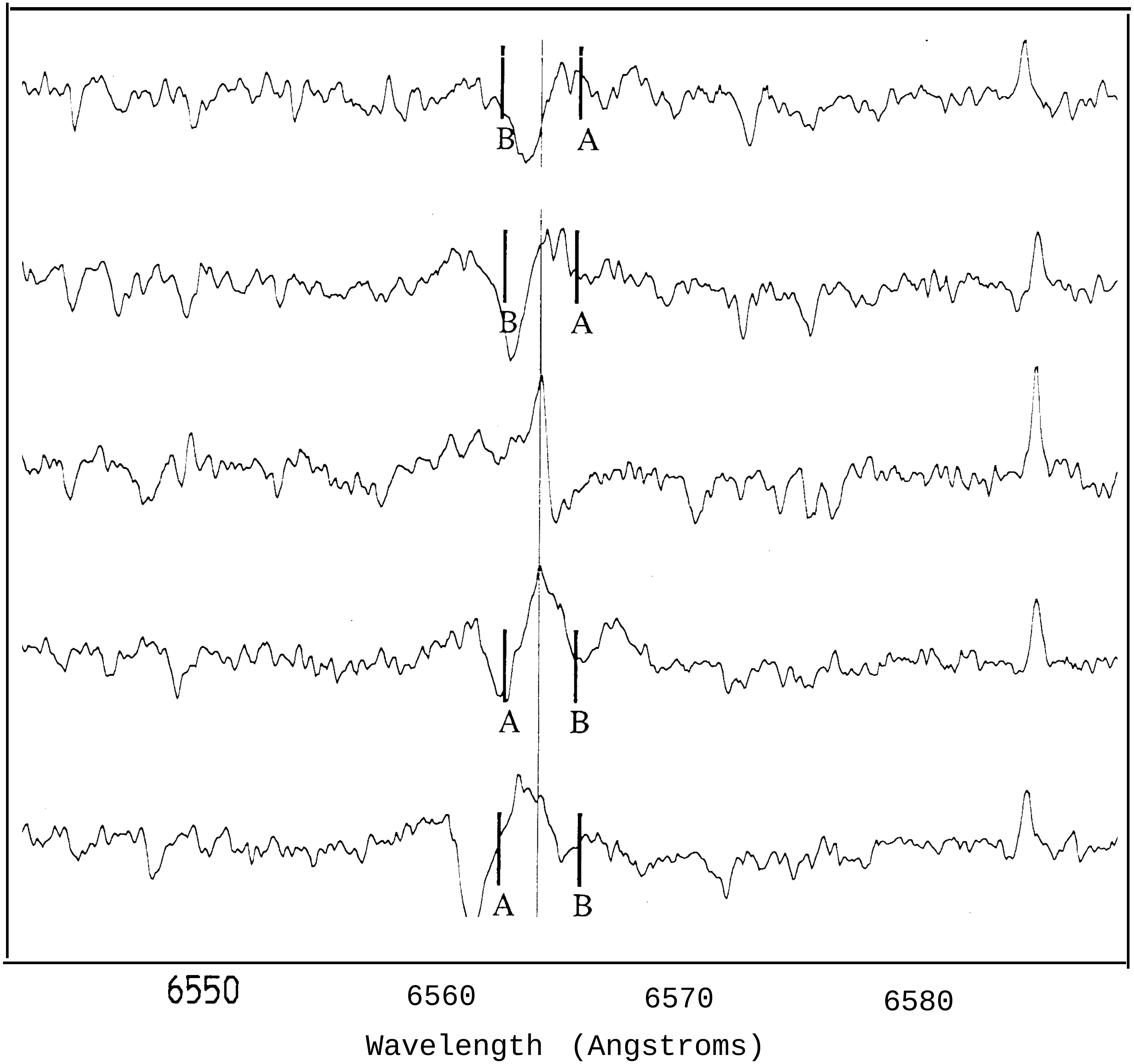
Figure 4. Spectral energy distribution of W134 in the visible and near-infrared. The solid curve is a 5450 K blackbody normalized to the stellar photometry at 1 band.

Figure 5. Positions of W134 A and B on the HR diagram. The overplotted isochrones and pre-main sequence evolutionary tracks are taken from Mazzitelli *et al.* (1989).

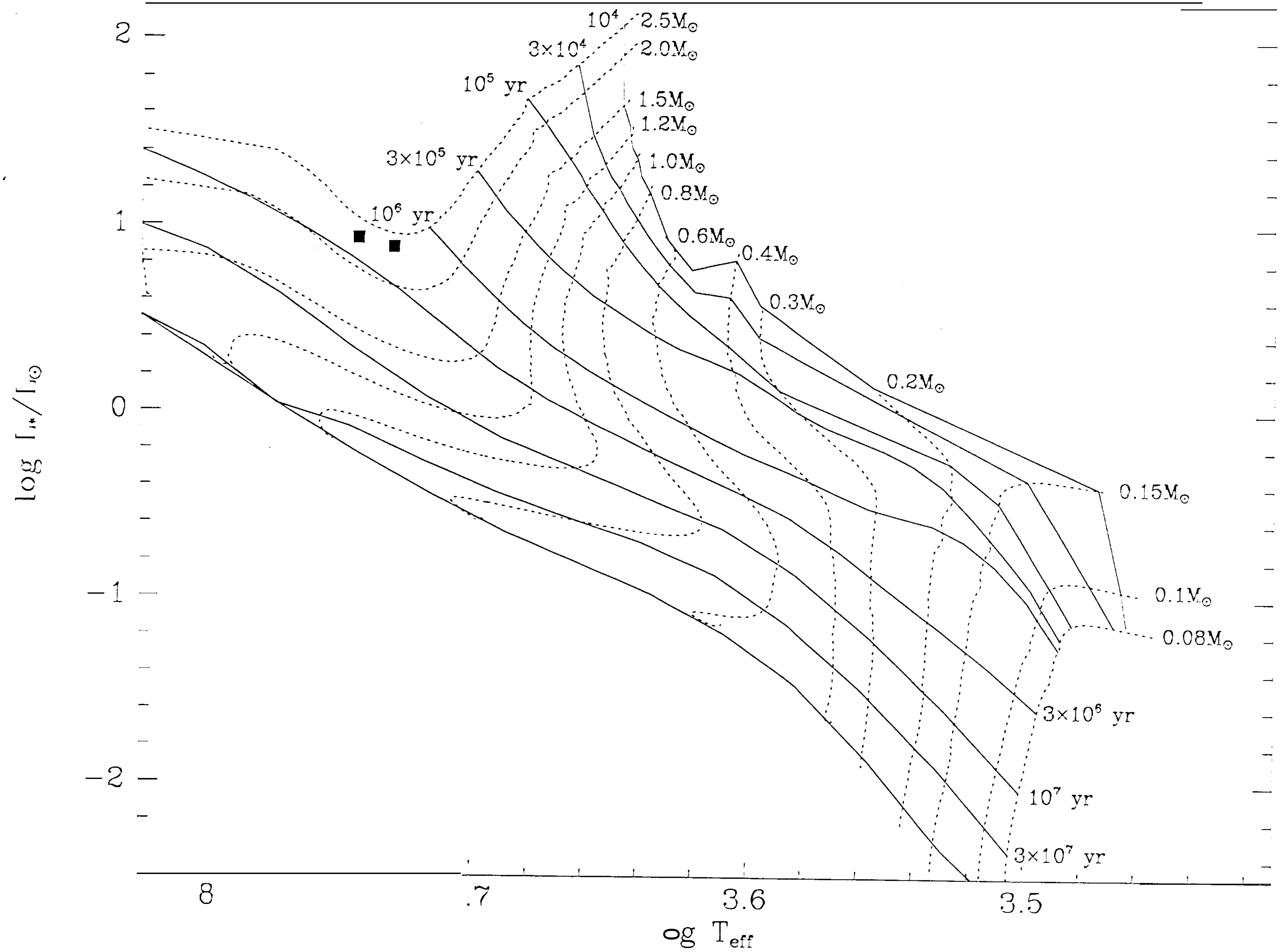

Separation Radial Velocity
Heliocentric Radial Velocity
Phase
0
0.2
0.4
0.6
0.8
1
200
100
0
−100
100
50
0
−50
−100



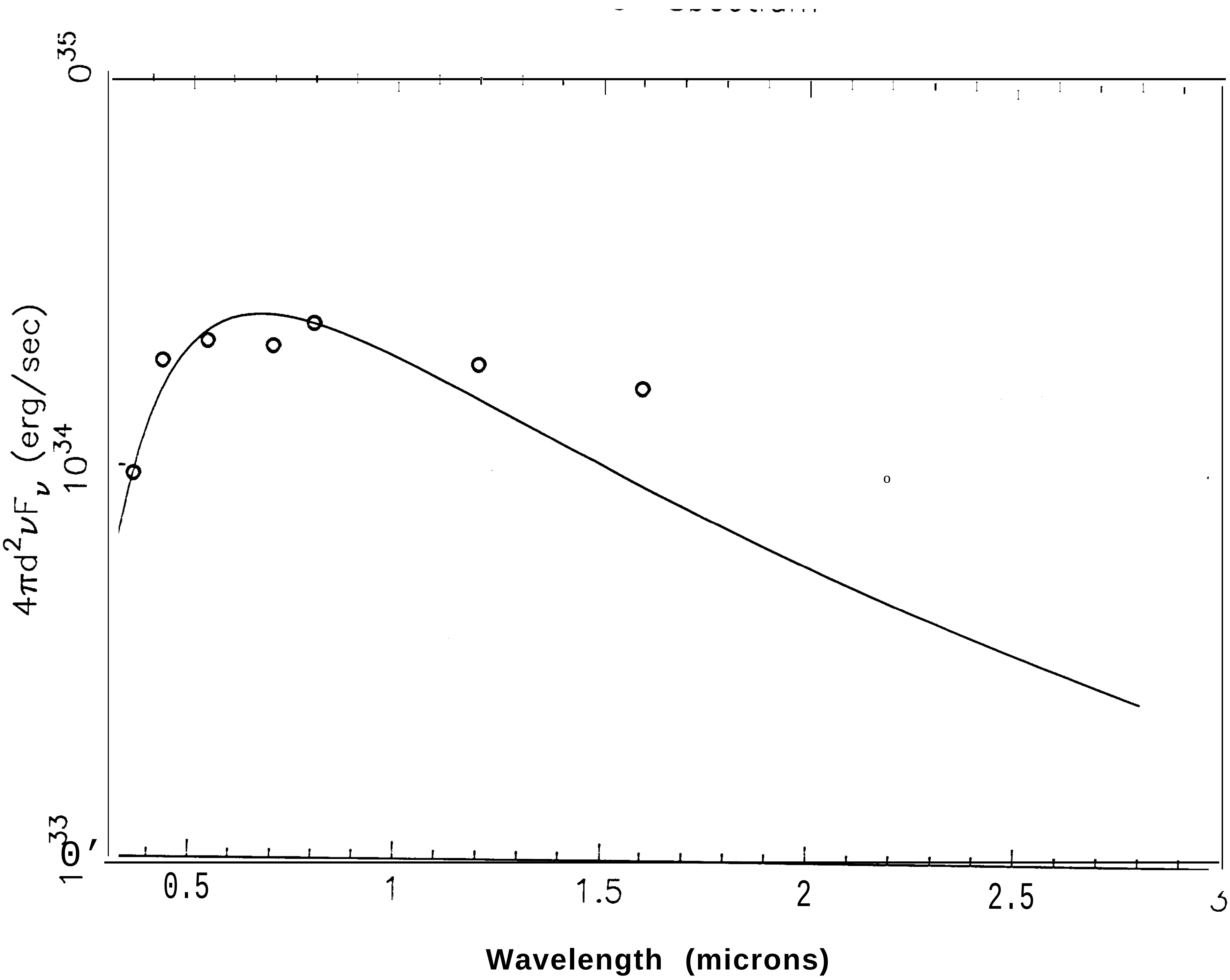
1.8
1.6
1.4
1.2
1
Ratio of CCF's
0
0.2
0.4
0.6
0.8
1
Orbital Phase



B
A
B
A
A
B
A
B
6550
6560
6570
6580
Wavelength (Angstroms)



10^4
$2.5M_\odot$
3×10^4
$2.0M_\odot$
10^5 yr
$1.5M_\odot$
$1.2M_\odot$
3×10^5 yr
$1.0M_\odot$
$0.8M_\odot$
10^6 yr
$0.6M_\odot$
$0.4M_\odot$
$0.3M_\odot$
$0.2M_\odot$
$0.15M_\odot$
$0.1M_\odot$
$0.08M_\odot$
3×10^6 yr
10^7 yr
3×10^7 yr
2
1
0
−1
−2
$\log L_*/L_\odot$
8
.7
3.6
3.5
og T_{eff}



10^{35}
10^{34}
10^{33}
$4\pi d^2 \nu F_\nu$ (erg/sec)
0.5
1
1.5
2
2.5
3
Wavelength (microns)

TABLE 1

Heliocentric Radial Velocity Observations of W134

Julian Date	Phase	V_{sep}	O - C	V_A	O - C	V_B	O - C	Note
244746S.95	0.365	111.1±2.5	-0.1	-27.8±1.7	0.8	83.3±2.3	1.2	C
2447469.02	0.376	121.0±2.9	0.7	-36.2±2.1	-3.2	84.8±2.4	-1.9	c
2447469.8S	0.511	168.353.1	-0.1	-.59.452.0	-2.8	10 S.%2.8	-2.2	C
2447470.01	0.532	163.0±4.1	-2.3	-56.8±1.4	-1.7	106.2±4.1	-.3.3	C
2447517.77	0.049	-164.5±6.0	-3.9					L
2447.531.82	0.260	0.0±15.0	-11.0	15.7±15.0	-4.7	15.7±15.0	-15.7	C
2447531.99	0.288	37.254.6	-2.3	1.8±1.2	-4.7	39.0±3.6	-6.8	CD
2447.546.S3	0.624	118.9±7.0	-1.4					L
2447.54S.S4	0.940	-157.1±3.4	-0.4					C
2447.551.87	0.417	145.7±7.0	-0..5					L
244'7579.57	0.792	-42.3±4.0	1.5	39.2±3.1	-8.0	-3.1±2.9	-6.7	CD
2447580.55	n.931	-153.8±2.3	-0.9					C
2447.581..59	0.094	-137.1±6.3	3.0	93.223.5	-1.2	-43.9±5.4	1.3	C
24475S3..5.5	0.403	138.6±3.2	0.0	-40.4±2.2	1.6	98.2±2.7	2.2	c
2447584.55	0.561	153.9±6.6	-2.7	-46.7±4.5	4.1	107.2±5.0	2.1.	c
2447585.5.5	0.718	32.0±3.6	-1.8	16.3±2.7	7.1	48.3±2.8	5.3	CD
2447586.55	0.875	-120.8±5.0	-1..5	82.4±3.3	-1.7	-38.4±4.0	-3.8	C
2447587.55	0.032	-164.1±2.8	1.1	107.6±2.6	1.0	-56.5±1.7	1.4	C
24475S8..55	0.1s9	-67.0±3.8	-4.3	56.3±3.1	-0.2	-3.7±2.6	2.3	C
24475S9.55	0.347	96.5±1.4	-0.2	-17.9±1.4	3.5	78.6±1.4	3.9	C

Key to Notes. C: Velocities derived from correlations of several echelle orders. L: Separation velocity derived from average of individual line center velocities. CD: Same as C with deblending of the correlation peaks. The zero separation data point was not used in fitting the orbit.

TABLE 2

Orbital Elements of w134

1' (days)	6.3532 ± 0.(101"2
$a \sin i$ ($R_\odot$)	21.2 ± 0.2
T_0 (JD)	2447472.9s5 ± 0.008
V_A (km s^{-1})	167.0 ± 1.'7
V_{W134} (km s^{-1})	25.8 ± 1.0
M_A/M_B	1.04 ± 0.()'2
$(M_A+M_B)\sin^3 i$ ($M_\odot$)	3.16 ± 0.10
T_E	1.589, 4.764

Note: T_0 is defined as the time when star A passes through the tangent plane of the sky as it moves toward the observer. V_A is the separation velocity amplitude and V_{W134} is the heliocentric radial velocity of the binary. The T_E are the predicted times (in days since T_0) when star A,B would eclipse the other.

TABLE 2

Orbital Elements of W134

P (days)	6.3532 ± 0.0012
$a\sin i$ ($R_\odot$)	21.2 ± 0.2
T_0 (JD)	2447472.985 ± 0.018
V_A (km s^{-1})	167.0 ± 1.7
V_{W134} (km s^{-1})	25.8 ± 1.0
M_A/M_B	1.04 ± 0.02
$(M_A+M_B)\sin^3 i$ ($M_\odot$)	3.16 ± 0.10
T_E	1.589, 4.764

Note: T_0 is defined as the time when star A passes through the tangent plane of the sky as it moves toward the observer. V_A is the separation velocity amplitude and V_{W134} is the heliocentric radial velocity of the binary. The T_E are the predicted times (in days since T_0) when star A,B would eclipse the other.

TABLE 3

Physical Parameters of W134 Components

Parameter	A	B
T_{eff} (K)	5510 ± 130	5350 ± 300
R_* ($R_\odot$)	3.2 ± 0.5	3.2 ± 0.7
L_* ($L_\odot$)	8.5	7.6
M_* (theory) ($M_\odot$)	2.3	2.2
Age (yr)	2×10^6	2×10^6
W_{6708} (mÅ)	197 ± 30	170 ± 30
W_{6708} (corr) (mÅ)	370	360
log[N(Li)]	4.1 ± 0.4	3.8 ± 0.4

Note: M_* (theory) is the mass indicated by the pre-main sequence tracks of Mazzitelli (1989) when the components of W134 are plotted on the HR diagram. The age of the components is also determined from these tracks. W_{6708} (corr) is the equivalent width of the lithium resonance doublet corrected for effects of the overlapping component continua.